Design of Shuttle Radar Topography Mapper (SRTM)

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ABSTRACT

A radar interferometric topography mapper designed to acquire digital elevation maps of the earth's surface from the Space Shuttle is described and its performance estimated. The system described is capable of acquiring a topographic map of all of the earth between 54°S and 60°N latitude to a height accuracy of 16 meters absolute. The system uses the previously flown SIR-C C-Band synthetic aperture radar system augmented by a second interferometric antennae deployed 60 meters from the Shuttle. The operation of the system, which requires the use of simultaneous two polarization radars operating with different polarizations with beam scanning, is described. Performance parameters limiting the vertical height accuracy of this system are described and the. implementation of solutions necessary to met the performance objectives are described.

1 INTRODUCTION AND REQUIREMENTS

The SIR-C/X-SAR system is a three frequency synthetic aperture radar system, operating at L, C- and X-Band which was flown on two 10 day Shuttle flights in April 1994 and October 1994[1,2]. During these missions, the combined SIR-C/X-SAR system demonstrated the ability to acquire calibrated two frequency polarimetric radar data as well simultaneous three frequency radar scattering maps of the earth's surface. The L-Band and C-Band systems employ an active distributed phase array antenna with a high degree of agility and during these same missions, they demonstrated the ability to acquire wide swath radar images using the SCANSAR mode of operation, SCANSAR is a radar technique which allows a larger radar swath to be acquired than that limited by range-doppler ambiguity limitations at the expense of reduced resolution. SCANSAR, was first demonstrated with the two SIR-C/X-SAR missions. The principle of this mode of operation is to illuminate an area on the ground long enough to acquire a synthetic aperture for the desired resolution and then move the illuminated beam to a different area across the swath to increase coverage. After this has been accomplished, the beam must move back to the original illuminated area before this area has left the illuminating beam. The SRTM system employs this technique with two simultaneous polarizations, each looking at a different area of the earth at a time. Due to potential interference between the polarizations, operation of each polarization must be at identical PRF's to avoid transmit interference between channels. This is illustrated in Figure 1. Also during the last three days of the second mission, the

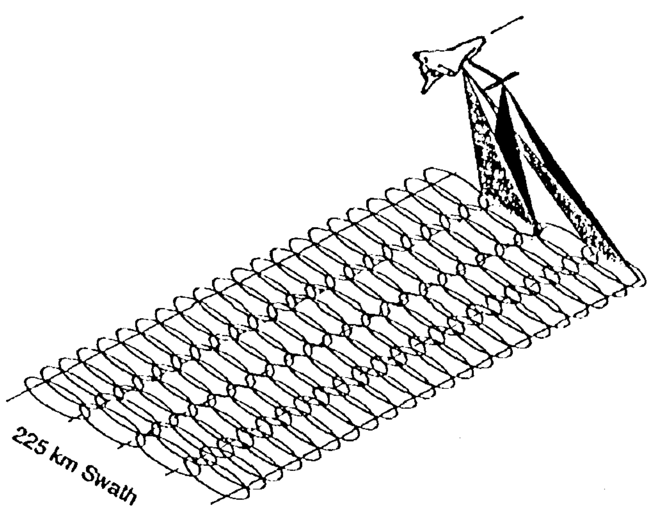


Figure 1 Double SCANSAR data acquisition

shuttle was programmed to fly nearly identical orbits which would allow the acquisition of interferometric radar data, The result of these repeat pass interferometric data takes was a demonstration of the capability to generate topographic maps from earth orbit wi th a radar system. Figure 2 shows a topographic map generated front two separate imaging radar passes over Long Valley, California. In this topographic map, areas of equal elevation arc shown in the same intensity. The outcome of these demonstrated capabilities - SCANSAR and derivation of topography for interferometry process - lead to the design of a radar topography mapper based on the SIR-C/X-SAR system which is described in this paper.

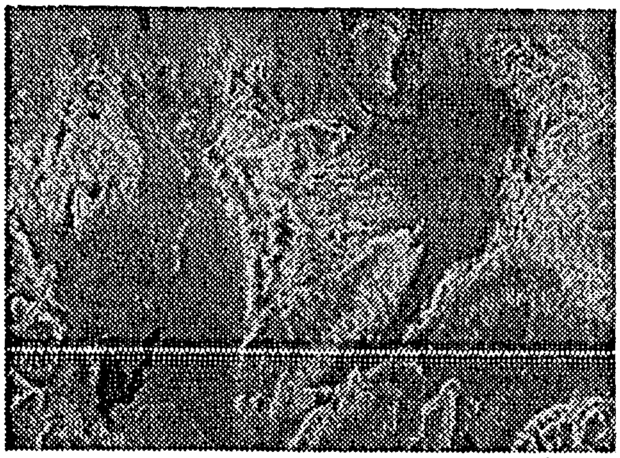


Figure 2 -Topographic Map of Long Valley, California generated from SIR-C Data

The requirement is to acquire a topographic map of as much of the earth's surface within the Shuttle resources, which translates to all the land mass between the latitudes of 54°S and 60°N over a 10 day period at a 57° orbit. The topographic mapping will be made to the requirements stated in the Defense Mapping Agency ITED-2 level. This requirement calls for a 90% vertical height accuracy of 10 meters relative over a scene and 16 meters absolute with a posting spacing of 30 meters. The Shuttle is only capable of staying in orbit for 10 days duration while providing the consumables required by the SIR-C system at a 57° inclination orbit. With the IO day repeat orbit, the required swath width for complete earth coverage is 218 Kilometers. Due to the antenna dimensions, the only way to attain this swath is to use SCANSAR techniques to cover this swath. In addition, duc to the accuracy requirements, both polarizations must be used simultaneously, each acquiring data from a different area on the ground in order to provide enough simultaneous looks.

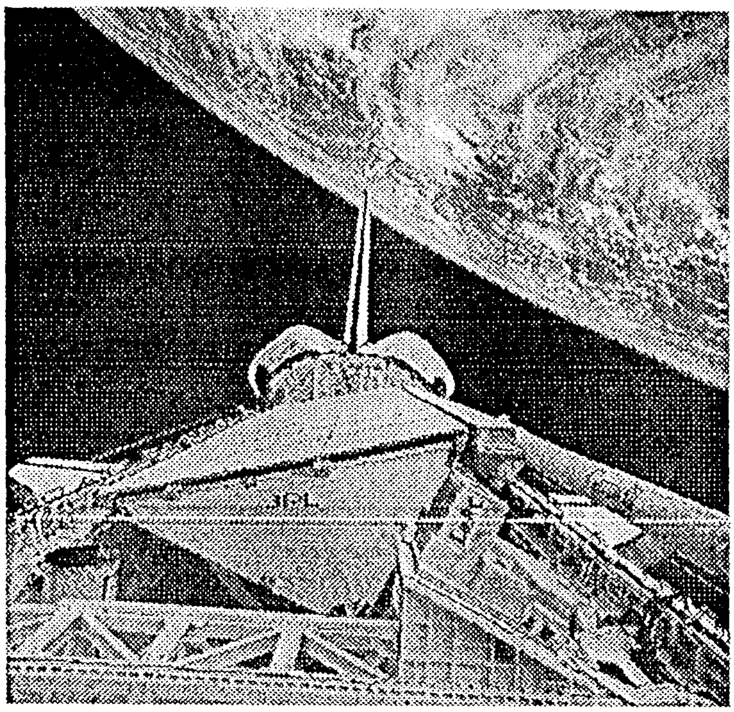


Figure 3 SIR-C and X-SAR in Shuttle Payload Bay

1.1 SIR-C C-Band System Description

The SIR-C/X-SAR system, as shown in Figure 3 consists of an antenna structure supporting the three antenna arrays and the SIR-C/X-SAR electronics in the payload bay, The antenna structure occupies most of the Shuttle payload bay with the digital routing electronics and data recorders located in the crew compartment. The SIR-C system operates at L- and C-Bands and each frequency uses a dual polarized distributed phased array antenna capable of electronically steering in both elevation (cross track) and azimuth (along track). The interferometer system described uses the C-Band portion of the SIR-C system and the description that follows will concentrate on this system. in addition to the ability to electronically steer the beam, the phased array antenna can introduce a phase function which will spoil the beam forming of the antenna and generate a beam which is wider than the ideal antenna pattern. This is a useful feature when it is desired to illuminate a larger portion of the earth's surface than a fully focused antenna.

The nominal system characteristics of the C-Band system for the interferometer mode arc tabulated in Table 1.

I'able 1
SIR-C System Characteristics for the SRTM Mission

Parameter	Requirement
Frequency	C-Band
Polarization	Horizontal and Vertical
Total Swath Width	218 Kilometers
SCANSAR simultaneous beams	.2- Onc at each polarization
SCANSAR beams pcr polarization	2
Spatial Resolution	30 Meters
Bandwidth	10 Mhz
System Noise Equivalent Sigma Zero	-35 dB
Transmit Power	1200 watts per polarization
Primary Antenna	0.74 meter by 12 meters
Secondary or Outboard Antenna	0.74 meter by 8 meters
Baseline	62 meters at a 45 Degree angle from vertical
Transmit Pulse Width	34 microseconds
Data Rate	180 Megabits per second in 4 channels
Final Product Resolution	30 meters by 30 meters

1.2 Interferometer requirements

The requirements to acquire topographic data from an interferometer pair is well known and documented extensively in the literature[3,6]. in order to avoid both signal shadowing and layover, the local angle of incidence must be centered around 45 degrees. in areas of shadow, it is not possible to unwrap the signal phase to derive local relative height since signals arc not present. I n areas of layover, those areas where the local topography slope equals or exceeds the radar incidence angle, it is also not possible to unwrap the phase to derive relative elevation between picture elements. The local incidence angle between the radar wave and flat terrain for the SRTM mission is limited to those angles between 32 and 58 Degrees. To acquire interferometer SAR data for the SRTM mission to the required height accuracy, it is necessary to have an antenna separation, or baseline, of greater than 50 meters. The baseline attitude is al an angle of 45 degrees from the local nadir direction and must be known with an accuracy of 11 arcseconds or better. The knowledge of lhc length of the baseline must also be known to an accuracy of 2 millimeters or better. The baseline separation and baseline attitude must bc known continuous during mapping operations and this information is required by the data processor for the calculation of absolute altitude from the center of the earth. The Shuttle position accuracy at all times must be known within 10 meters in the horizontal plane and 1 meter in the vertical plane.

2 MISSION DESCRIPTION

The SRTM mission consists of 10 days of data acquisition with the Shuttle on a 10 day repeat orbit. The Shuttle orbit is a nominally circular orbit at a 57 Degree inclination. The existing antenna mounting on the Shuttle and the boom deployment requi rcs that the Shuttle attitude be at an angle of 59 degrees from the wing to wing line and local nadir. The boom then deploys at a 45 degree angle with respect to nadir away from the earth, This places the star trackers in view of deep space. In order to illuminate in the northern direction, then the Shuttle must fly with the tail forward. The area covered by this orbit is (hen from 54°S to 60°N. It is planned to acquire interferometric radar data starting at a distance of 200 kilometers from each coastal crossing and ending at 200 kilometers after the land to water crossing, The minimum swath requirement at the equator is 225 kilometers allowing for 7 kilometers of overlap between orbital passes. As the Shuttle latitude increases, the required swath decreases allowing a reduction in the number of repeat passes for higher latitudes. Over this coverage, the altitude of the Shuttle varies between 233 kilometers over the equator to an altitude of 247 kilometers at the top of the orbit, Over this altitude range, the radar system can operate at a constant set of pulse repetition frequencies with adjustments in the data window position at the lower altitudes and minor look angle adjustments at the higher altitudes. Over the 159 orbits of data acquisition, a total of 80 hours of data wilt be acquired. This is sufficient to acquire interferometric SAR data over both ascending and descending. passes to cover each spot on the earth between these latitudes at least two times. After data acquisition, the topographic maps will be produced over a one year interval at a data processing center at JPL.

3 SYSTEM DESCRIPTION

The primary SIR-C L and C-Band systems will remain basically unchanged as they were flown in the previous two flights except for some minor modifications to adapt the existing hardware to the interferometric mission. Since the interferometer will operate as a single-pass fixed baseline instrument, a second set of receive only antennas, one at C-Band and the other at X-Eland will be added to the equipment complement. The new antennas which will be referred to as the Outboard Antenna Subsystem (OAS) will be mounted on an independent support structure which will be stowed during launch and landing and deployed via an extendible mast during on-orbit operations. Fig 4 shows the on-orbit configuration. The size of the outboard antennas were chosen to satisfy not only the performance requirements of the interferometer but also took into account the available space within the constraints of the shuttle cargo bay. The outboard C-Band array is 0.75meter wide by 8 meter long while the X-Band array is 0.4 m. wide by 6 m. long. The mast which provides the baseline separation between the main and the outboard antennas is contained in a 1.4 m by 3 m cylindrical canister when stowed and deploys to 60 m. when fully extended. It is an actively driven mast which has the advantage of being fully rigid and mechanically stable at any length during deployment. As with the antennas, the maximum length of the mast was dictated by the available space Because of the importance of maintaining precise geometric relationship between the main and outboard antennas over the expected thermal conditions during the mission, the structural components of the mast will be composed of graphite epoxy in combination with metallic end fittings in order to achieve a nearly zero coefficient of thermal expansion (*cte*). A previous versions of this mast has exhibited a *cte* of 0.2ppm/°K. Fig.5 shows a 30 m. version of an extendible mast which was developed for the Space Station by AI:C-Able Engineering Company. The 60 m. SRTM mast will be provided by the same source. The

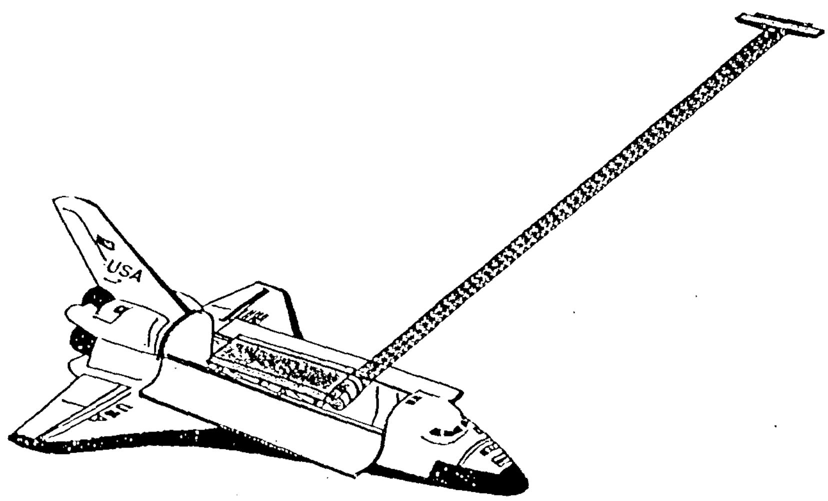


Figure 4 SRTM Interferometer Configuration

OAS mounting structure will likewise be constructed from composite materials (o achieve the desired thermal stability.

The outboard C-Band antenna array will be based on the same dual- polarized design as the main antenna, The elevation aperture is formed by 18 elements while the azimuth aperture will be subdivided in into 12 subapertures. Each panel will contain LNAs and phase shifters for H and V polarization. This semi-active (receive only) configuration will provide not only the electronically steerable beam needed for SCANSAR but also makes more effective use of the sensitivity of the low noise amplifiers. In order to avoid the losses in the GO m. separation between the outboard antenna and the rest of the system, the received echoes will be delivered via a fiber optic link "down the length of the mast to the main receiver and data subsystem which arc located in the cargo bay. A preliminary analysis of the stability of the deployed antenna revealed, two potential sources of baseline errors. The first is a static misalignment error caused mainly by gravity unloading and thermal gradients on the mast, the other is dynamic motion at the tip of the mast in response to shuttle attitude control jet firing,. Consequently, two methods will be incorporated in SRTM to correct for these errors. Static misalignment bet}!'ccn the main antenna and the outboard antenna will be determined by a combination of optical instrumentation and by examining the radar relative strength in the outboard antenna co-alignment beams. Compensation for the dynamic motion of the outboard antenna will also be in two ways: First, an error signal derived from a misalignment of the two antenna beams will be used to automatically cause the outboard antenna to lock on to and track the main antenna beam. Second, the motion of the outboard antenna will be measured and recorded via a precision optical tracker throughout the mission and the data used for compensation during processing.

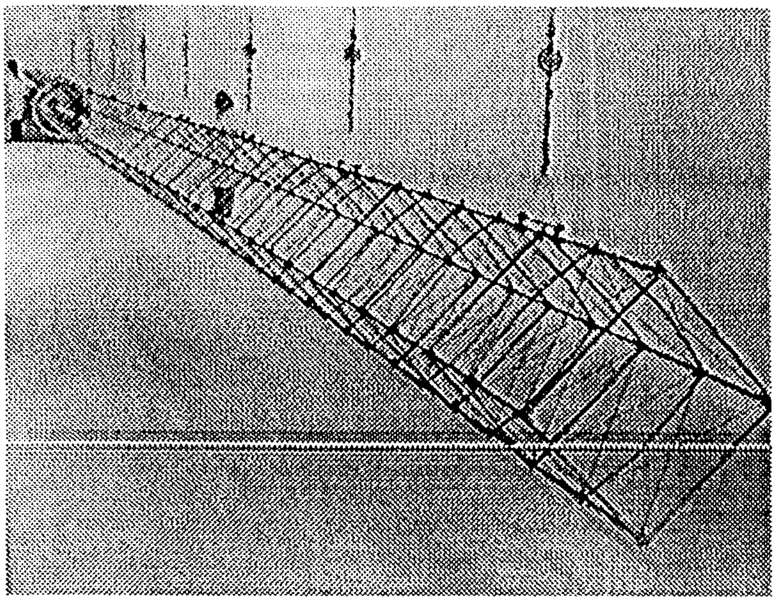


Figure S Deployable Mast

3.1 Met rology

The function of the metrology subsystem is three fold. The first is to measure the characteristics of the interferometer baseline to a high accuracy. The second is to calculate the position of the Shuttle while the third is to provide the interferometer system with a precise time base to relate all measurements to a common timebase. The absolute baseline attitude is being measured with a combination of sensors. The first is a star tracker mounted on an optical bench at the base of the main antenna. The star tracker provides an inertial reference unit absolute attitude updates. A camera system, based on a star tracker senses the relative motion of the outboard antenna with respect to the optical bench by observing three light sources (LED's) mounted on the outboard antenna. The absolute position of the Shuttle is measured by the GPS system which uses an antenna mounted on the outboard antenna structure, The GPS system also provides the common time base to which all measurements arc tied to. This includes the attitude measurement hardware and the radar system relative timebase.

3.2 On-board Data handling and Storage

The raw radar signals from four SIR-C receiver channels, two channels (HH and VV) each from primary and outboard antennae, arc digitized into four 8-bit data with each channel at an output rate of 45 Mbits/sec. This function is performed by four Digital Data Handling Assemblies (DDHA's). These four channel data arc then fed into the Digital Data Routing Electronics (DDRE). The DDRE multiplexes the data into onc single 180 Mbits/sec data stream to be recorded by onc of the three Payload High Rate Recorder (PHRR's). In addition to the above functions, the DDRE also receives X-SAR digitized data at 45 Mbits/see from the X-SAR Data and Control Electronics (DCE). The DDRE can simultaneously route any single realtime or playback data to the ground via the TDRSS link. During the first two missions, X-SAR provided onc channel data and used onc PHRR to record its data. SIR-C used another recorder and the 3rd recorder was reserved as backup. Written at 180 Mbits/sec (SIR-C multiplexed data rate), the digital tape cassette for the PHRR can record up to 30 minutes on a single cassette, or at about 300 Gbits (about 40 Gbytes) per cassette. The same capacity allows X-SAR to record up to 2 hours of data,

Two modifications will be made to the existing on-board data handling and storage hardware for the SRTM. See Fig. 6 for the modified hardware functional block diagram. (Note that the shaded area is the existing DDRE hardware and that the SIR-C DDHA's, PHRR's, and X-SAR DCE-1 arc existing hardware but not part of DDRE.) The first modification is to accommodate onc additional channel of X-SAR data from its outboard antenna/receiver channel, as delivered by its Data and Control Electronics-2 (DCE-2), with the existing channel from the primary system labeled as DCE- 1. The two 45 Mbits/see data will now be multiplexed by the modified DDRE into a single 90 Mbits/sec data stream for recording onto the PHRR. In addition, the DDRE will maintain the capability of routing of any of the 45 Mbits/sec input data channels (four from SIR-C and two from X-SAR) to the Shuttle KuSP for live down-link.

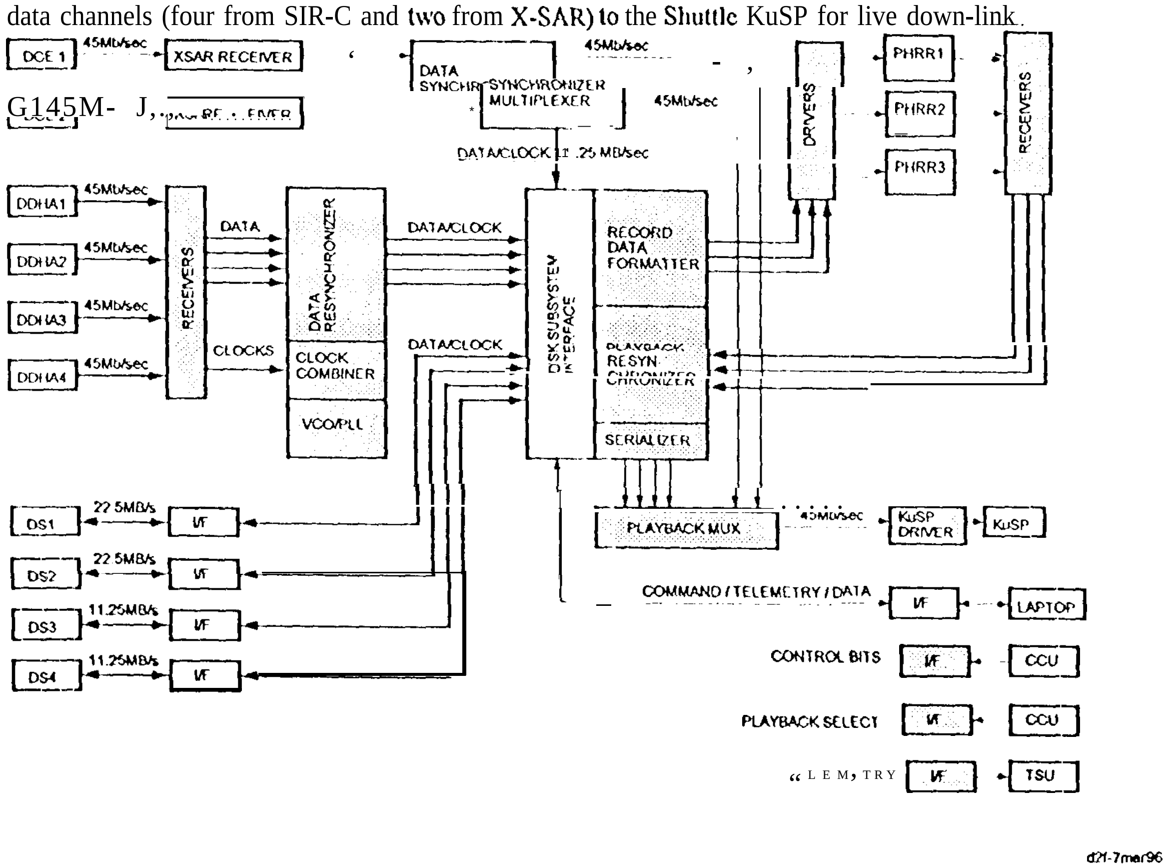


Figure 6 Data System Functional Diagram

The second modification is to address the most vulnerable part of the SIR-C flight system by strengthening its reliability and redundancy. Part of the concern is based on the failure of onc of the PHRR's during the second mission that lead to loss of data and operation time. Given the stringent requirements of the SRTM, that very area except the high latitude portion of the world would be visited only twice (one in ascending and the other in descending), any malfunction of the data handling and storage hardware means failure to acquire data for that portion of the world, Also during the first Iwo missions, the PHRR and tape management, including recorded data playback from the tape, was performed with complicated and often not precise ground software with intensive interaction between crew and ground staff. The number of tapes planned to be used for the SRTM will be 270, about 28% more than each of the previous missions. The full utilization of each tape is critical for mission success. There is a strong desire to improve and simplify the recorder and tape management, Thirdly, it is expected that there will be a fcw data takes expected to be longer than 30 minutes. The existing system without modification will lead to data loss of portion of the data take duc to tape change in between. It is critical to prevent that type of data loss and other possible data loss duc to unexpected failure. Thus the second modification has three objectives: 1) to increase the reliability; 2) to simplify PHRR and tape management; 3) to increase the utilization of each tape by recording at full capacity, and 4) to eliminate data loss due to tape changes.

The preliminary kcy design to accomplish the above objectives is to insert high density high speed disk farms, a relatively ncw technology, into the digital data handling and storage hardware as the primary but intermediate recording hardware. The PHRR's will still serve as final data storage. There will be four disk farms, or Disk Subsystems (DS-1 to DS-4), each is sized to be about 60 Gbytes, usable storage size from ten 9-Gbyte disk drives with partial redundancy. Note that each disc farm can store more than onc cassette worth of data (40 Gbytes). Two of the disk farms will be reserved for SIR-C usc and two for X-SAR. During operation, SIR-C data will be constantly written to onc of the disk farm and X-SAR to another. Once the disk farm has store onc cassette worth of data, the data will be written to another disk farm automatically. This automatic hand-over will prevent any data loss which otherwise would be created by having to change tapes. While the second disk farm is being written, the onc cassette worth of data on the disk farm will be dumped at high speed to onc of the PHRR's. This approach substantially reduces the wear and tear of the PHRR's by reducing the number of turn on/off cycles, a primary suspect for causing the PHRR to fail during the second mission, which also allows each cassette to record to its full capacity. Also with this approach, four disk farms and three recorders arc always shared by SIR-C and X-SAR. Considering in the worse case that three of the four disk farms and two recorders would be used during the mission, there will always be onc hard spare of onc disk farm and onc PHRR in the worse case and more hard spares most of the time. It improves the reliability of the system considerably. However, this improvement requires, in addition to the disk farms, a more sophisticated data controller to manage the disk farms, PHRR's and the tapes. The design calls for the implementation of data quality and control software to reside on a laptop (Thinkpad) computer for such operation. The software will be responsible for monitoring the usage of disk farms, automatic switching of disk farms, and dumping fully stored disk farm data to any of the available PHRR's. The change of cassettes will still rely on the crew. The software will also allow forwarding selected portion of the data on the disk farm for live down-link. In addition to these data handling and routing functions, it is also required that the software control the PHRR's and acquire a portion of the recorded data (by read-after-write) during the data dump to ensure the data recorded on each cassette arc of good quality. This is addressing the occurrence during the previous two missions where a small amount of data was successfully recorded to the tapes but found to be of poor quality during the playback for image processing after the missions. Tentatively, there will also be software to grab a portion of data on the disk farm for quick analysis of radar performance and beam alignment, in case the live down-link opportunities arc not frequent enough or not available.

This modified and enhanced design will significantly improve the reliability and flexibility of the data storage subsystem and eliminate possible data loss that cannot be circumvented with the existing hardware for the expected mission requirements.

3.3 Data Processor and Topographic map generation

After the end of the mission, the digital [apes will be first duplicated and the data tapes sent to their respective Ground Data Processing centers. The processing procedure to generate the topographic maps is basically as follows. First, the radar data from each of the two interferometric channels is processed to generate phase maps. A difference phase map is then produced for an entire pass between ocean coastal crossings. Using the baseline angle and length information from the metrology system, a relative height map is then obtained from a phase unwrapping algorithm, The absolute height maps arc then generated after calculation of the ocean heights derived from TOPEX ocean models and tide tables.

4 EXPECTED PERFORMANCE

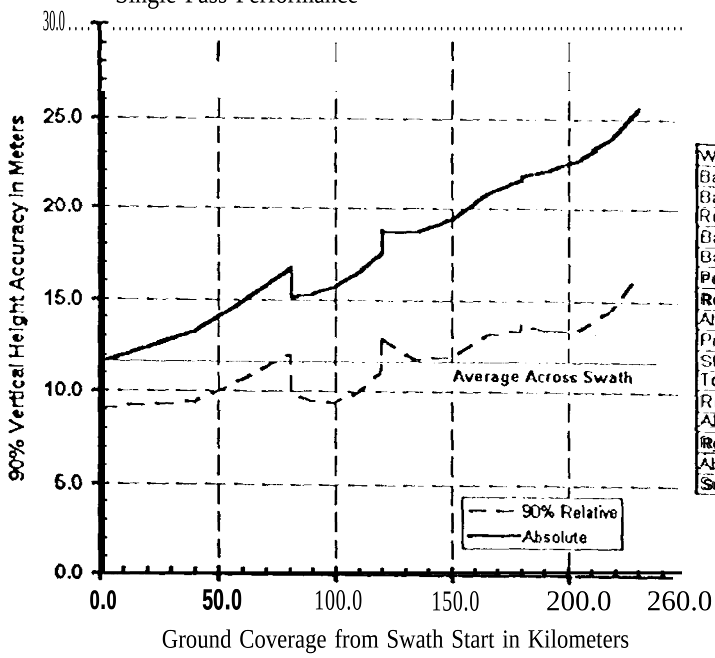
The expected accuracy of the SRTM system depends on the error sources inherent in the measurement process. These error contributors arc:

1) Radar System Noise
2) Baseline Metrology errors
3) Position errors .
4) Propagation errors
5) Processing errors
6) Terrain topography effects

The components of radar system noise, which have&n verified by the first two missions of SIR-C, arc a) thermal noise, b) decorrelation noise, c) quantization noise, d) range and azimuth ambiguities and e)

SRTM Vertical Height Accuracy

Single Pass Performance



Wavelength	0.0566	Mtrs
Baseline Length	62	Mtrs
Bandwidth	10	MHz
Resolution	30	Mtrs
Baseline Angle	45	Deg
Baseline Angle Error	11.2	ArcSec
Position Error	0.8	Mtrs
Reference Error	0.85	Mtrs
Atmospheric Error	0.3	Mtrs
Processing Error	0.8	Mtrs
Slant Range Error	0.3	Mtrs
Topography Related	0.7	Mtrs
Relative Accuracy Single Pass	11.8	Mtrs
Absolute Accuracy Single Pass	18.2	Mtrs
Relative Accuracy	8.3	Mtrs
Absolute Accuracy	12.8	Mtrs
Surface Brightness	-55	dB

Figure 7 Expected SRTM Vertical **Height** Accuracy

integrated sidelobe error noise. Baseline metrology errors arc measurement error of baseline attitude and length. Position errors arc errors in estimating orbit location as well as errors in estimating the location of the antenna phase center. Propagation errors arc tropospheric and ionospheric induced errors. Processing errors include interchannel misregistration errors and interpolation and geolocation errors. Terrain topography errors include height posts Vs the average height over a resolution cell. The expected height